Soil quality standards and guidelines for forest sustainability in northwestern North America☆

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Abstract

Soil quality standards and guidelines of the USDA Forest Service were some of the first in the world to be developed to evaluate changes in forest soil productivity and sustainability after harvesting and site preparation. International and national development of criteria and indicators for maintenance of soil productivity make it imperative to have adequate threshold variables within the USDA Forest Service. In the Pacific Northwest, soils range from fine-textured Andisols to coarse-textured skeletal Inceptisols. Forest types encompass the highly productive coastal rain forest to marginally productive, dry, cold sites in the interior mountains. Constant values to detect detrimental disturbances within the soil quality guidelines are routinely applied across diverse soils and timber types and include diagnostic criteria for evaluating management-caused changes to soil productivity. Research information from short- or long-term research studies supporting the applicability of disturbance criteria is often lacking, or is available from a limited number of sites which have relatively narrow climatic and soil ranges. In this paper we calculated changes in soil carbon, nitrogen, erosion, and cation exchange capacity using threshold variables from the Regional USDA Forest Service Soil Guidelines to assess their applicability across diverse landscapes. Soils were selected from a climatic and elevational gradient in the Pacific Northwest. Application of selected USDA Forest Service standards indicate that blanket threshold variables applied over disparate soils do not adequately account for nutrient distribution within the profile or forest floor depth. These types of guidelines should be continually refined to reflect pre-disturbance conditions and site-specific information. Published by Elsevier Science B.V.

Keywords: Soil productivity; Threshold values; Detrimental disturbance

1. Introduction

Forest managers are increasingly using the terms 'sustainable forests', 'sustainable forestry practices', and 'long-term productivity'. These terms are used interchangeably, but usually have different meanings for different forest users depending on ecosystem perspective, use, and spatial and temporal scales

(Amaranthus, 1998). Although there are many terms and definitions for a sustainable forest, soil productivity is a key factor to maintaining ecosystem function (Powers et al., 1998). On public lands in the USA, maintenance of soil productive capacity is a common objective, which is governed by the Multiple Use and Sustained Yield Act of 1960, the National Environmental Policy Act of 1969, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976. Forest industry members of the American Forest and Paper Association must satisfy the Sustainable Forestry Initiative for soil productivity by using strategies appropriate to soil, topography, and climate (American Forest and Paper Association, 1994). In Canada, the Forest Practices Code developed by the British Columbia Ministry of Forests establishes mandatory requirements for planning forest practices, including methods to assess hazards and soil degradation; a rehabilitation guide is also provided (Forest Practices Code of British Columbia, 1995, 1997).

Soil productivity monitoring protocols are being developed as indicators of sustainable forest management on broad national levels (Ramakrishna and Davidson, 1998). On federal lands in the USA, post-disturbance monitoring is used to assess changes in soil productivity or quality (Powers and Avers, 1995). Other ownerships are not under the same regulations as federal lands, but many states have, or are considering, methods to measure changes in soil quality (Powers et al., 1998). The important role of soil productivity to sustained forestry is clear, but which soil properties to monitor as indicators of forest sustainability are not (Burger and Kelting, 1998; Staddon et al., 1999).

For forests to be sustainable, soil quality — the inherent capability of soil to support vegetative growth — must be maintained (Power and Myers, 1989). Evaluating soil quality is difficult because of the diversity of soil properties to be measured, appraisal techniques, and soil uses. Proposed first-order soil physical property assessments of soil quality are infiltration, available water holding capacity, and soil depth (Papendick and Parr, 1992). Chemical indicators include pH, salinity, cation exchange capacity, organic matter, and any site-specific factors (i.e. heavy metals) (Karlen and Stott, 1994). Suggested biological indices

are soil enzyme activity (Dick, 1992), soil fauna (Stork and Eggleston, 1992), or microbial activity (Powlson et al., 1987). These variables have been suggested mainly for agricultural soils. Powers et al. (1998) proposed measuring a small set of indices (soil strength, anaerobic incubation of organic matter, and soil invertebrate activity) to establish baseline soil quality conditions in more variable forest soils.

In diverse forest ecosystems, model simulations may be a more effective method for determining changes in soil quality (Burger and Kelting, 1998). For instance, water infiltration and retention can be measured directly or predicted from soil bulk density, organic matter content, or conductivity. Development of relationships among most measurable soil properties and soil functions is not widely available, but there are several models (e.g. WEPP, EPIC, NLEAP) which simulate them (Doran and Parkin, 1994). Harvesting impacts on soil organic matter characteristics and ecosystem function have been modeled using FORE-CAST (Morris et al., 1997). Although there are a myriad of methods used to measure soil changes associated with anthropogenic or natural disturbances, the information that relates the measured variables to soil processes, vegetative growth, or disturbance regime is limited. Process models can be constructed to substitute for soil monitoring, but to date information is lacking on vegetation-soil systems (Burger and Kelting, 1998).

Efforts to construct definitive soil quality/sustainability standards and guidelines are still in their infancy and reflect the wide diversity of soil properties and climate conditions in forest ecosystems. Most current standards and guidelines are based on easily measured soil properties and/or readily available climate and site information. For example, guidelines for surface erosion are based on topography, rainfall duration and intensity, infiltration, and vegetative cover (Wischmeier and Smith, 1978; Dissmeyer and Foster, 1985; Elliot and Hall, 1997). Soil compaction guidelines were developed to account for either an increase in bulk density or decrease in porosity. Visual criteria are used to quantify puddling, soil displacement, and sometimes compaction (Miller and Sirois, 1986; Aust et al., 1998).

One of the earliest soil quality standards and guidelines were developed by the US Forest Service (USFS) to act as a first warning of reduced forest site pro-

Table 1
USFS soil quality standards for the Northwest USA

Disturbance variable	USFS region[a]	Thresholds
Physical properties		
Soil displacement		
	1	Loss of 2.5 cm of any surface horizon, usually the A horizon
	4	Loss of either 5 cm or $\frac{1}{2}$ of the humus-enriched topsoil, whichever is less
	6	Loss of 50% of the A horizon
Compaction		
	1	Bulk density increase of 15%, usually the A horizon
	4	Reduction of >10% soil porosity or a doubling of soil strength
	6	15% bulk density increase (volcanic soils: 20%)
Rutting and puddling		
	1	Wheel ruts at least 5 cm deep
	4	Ruts or hoof prints in mineral soil or Oa horizon
	6	Ruts to at least 15 cm depth
Erosion (surface)		
	1	Visual evidence of detrimental soil loss and maintenance of minimum ground cover based on local conditions (soil loss should be <2–4 t/ha/year)
	4	Establish local minimum ground cover guidelines to limit erosion (not to exceed the natural rate of soil formation)
	6	Visual evidence of detrimental soil loss and maintenance of minimum ground cover based on erosion hazard class (not to exceed the soil formation rate)
Soil cover		
	1	Enough cover to prevent erosion from exceeding natural rates of formation
	4	Too little to prevent erosion from exceeding natural rates of formation
	6	less than 20% cover on sites with low erosion hazard ratings, 30% for moderate, 45% for high, and 60% for very high (for year 1 after disturbance)
Organic matter		
	1	Local guidelines developed based on ecological type
	4	Local guidelines developed based on ecological type
	6	Local guidelines developed based on ecological type
Burned conditions		
	1	Forest floor lost and A horizon has intense heating
	4	Loss of either 5 cm or $\frac{1}{2}$ of lifter layer, whichever is less
	6	Mineral soil oxidized and next 1.5 cm blackened due to charring of organic matter

[a] 1, Northern Region; 4, Intermountain Region; and 6, Pacific Northwest Region.

ductivity and sustainability after harvesting and subsequent site preparation. These guidelines represent one of the first attempts at either a national or international level to quantify a threshold of soil changes which are detrimental to forest soil productivity. The general concepts and the basis for the various guideline categories are described by Griffith et al. (1992). Threshold values (quantifying change) were based on the assumption that site quality will be maintained if <15% of an area is detrimentally impacted after disturbance (Powers et al., 1998). Although soil quality guidelines vary for each Forest Service Region, they generally fall into four categories: (1) soil physical properties; (2) soil erosion; (3) soil organic matter content; and (4) fire effects. Guidelines for three Forest Service Regions in the Pacific Northwest are briefly described in Table 1 and are further discussed in Powers et al. (1998).

As currently formulated, these Forest Service soil quality sustainability guidelines are uniformly applied across each USFS Region regardless of soil or ecosystem properties. However, Burger (1997) maintains that indicators of soil quality must be site- and soil-specific. For example, soil quality indicators for a

young, drought prone Entisol should be different than those used for monitoring an older, poorly-drained Alfisol (Burger and Kelting, 1998). Therefore, the purpose of this paper is to evaluate the effectiveness of applying uniform soil quality guidelines and threshold values over diverse forest landscapes in the Pacific Northwest. The guidelines selected for evaluation were soil displacement, erosion, and burned conditions. Each of these guidelines represent one or more soil function, and are monitored through either empirical measurements or visual assessments.

Soil displacement is the loss of surface horizons (forest floor and mineral topsoil) by a combination of harvesting disturbance and mechanical site preparation, and is an indicator of soil organic matter and nutrient loss. Erosion is a measure of soil movement induced by wind or water after the initial harvest/site preparation impact. Similar to soil displacement, erosion addresses changes in soil organic matter and nutrient content, but also possible sedimentation in adjacent streams and lakes. The major impact of detrimental burn conditions on soil productivity is through the loss of organic matter and volatilization of soil nitrogen (N) (DeBano et al., 1979).

Disturbance impact on soil organic matter is a factor in all three of these guidelines. Forest floor and mineral soil organic matter have important roles in nutrient availability and cycling, gas exchange, water supply, soil structure, and disease incidence (Harvey et al., 1987; Powers et al., 1990; Blake and Ruark, 1992; Henderson, 1995; Jurgensen et al., 1997). Studies from the Northwest USA and elsewhere have shown that loss of organic matter after harvesting or site preparation can have profound effects on soil physical, chemical and biological properties, and reduce soil productivity (Perry et al., 1989; Powers et al., 1990; Dyck et al., 1994; Everett et al., 1994; Harvey et al., 1994; Henderson, 1995; Jurgensen et al., 1997). Three important components of organic matter (C, N, and CEC), were used to estimate variability in Soil Quality Guidelines applied across different climates and soil types. Three representative soils from three USDA Forest Service Regions (Region 1 [Northern], Region 4 [Intermountain], and Region 6 [Pacific Northwest]) were used in this appraisal (Fig. 1). These soils cover a wide range of taxonomic and climatic conditions found in forests of the Pacific Northwest (Table 2).

2. Methods

2.1. Total soil pools

Total mineral soil C, N, and CEC pools were estimated for each soil using Natural Resource Conservation Service (NRCS) soil survey profile descriptions and analyses (Sparks, 1996). Soil horizon chemical and CEC data were extrapolated to a consistent soil depth of 1 m using horizon bulk density values and rock-fragment content. Since the soil survey descriptions did not contain any information on forest floor horizons, C and N values in the forest floor were obtained from various research studies being conducted on similar soils each region (Page- Dumroese, unpublished data). Cation exchange capacity of the forest floor and mineral soil was estimated using the CEC/loss-on-ignition regression equations for forest floor developed by Kalisz and Stone (1980) and Meyer et al. (1994).

2.2. Application of soil threshold guidelines

Threshold values for soil displacement, detrimental burning, and erosion from the three USFS Regions were applied to each soil. A disturbance (e.g. harvesting, prescribed fire) is assumed to be detrimental to soil productivity and sustainability if any one of the threshold values are exceeded on >15% of the area. All values are expressed on a hectare basis.

2.2.1. Soil displacement

Region 1 — *loss of 2.5 cm or more from any surface horizon, usually the A horizon*. We assumed all the forest floor is displaced.
Region 4 — *loss of either 5 cm or one half of the humus-rich A horizon, whichever is less*. We assumed all of the forest floor is displaced.
Region 6 — *removal of >50% of the A horizon*. We assumed all of the forest floor is displaced.

2.2.2. Detrimental burning

Region 1 — *forest floor is destroyed and A horizon has had intensive heating*. We assumed 50% of the C, N, and CEC in the A horizon is lost (volatilized).
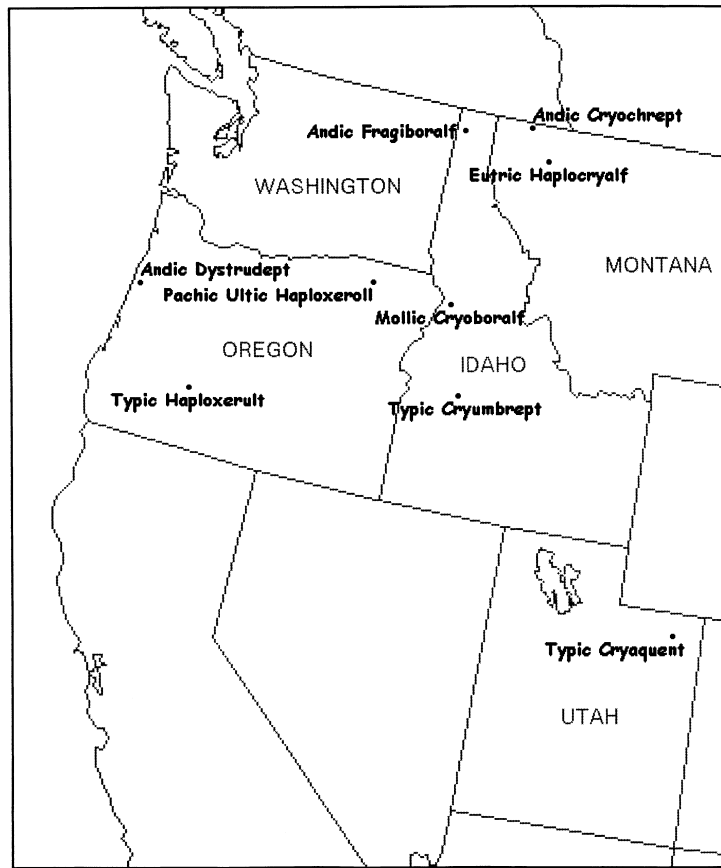Region 4 — *loss of either 5 cm or one-half of the*

Fig. 1. Location of selected representative soils in the northwestern USA.

Table 2
Site characteristics of representative soils from Regions 1, 4, and 6 used in this study

USFS region and soil subgroups	Slope (%)	Elevation (m)	Mean annual precipitation (mm)	Potential natural vegetation
Region 1 (Montana & Idaho)				
Eutric Haplocryalf	15–60 (20)[a]	1000–2000 (1460)	650–870 (700)	*Pseudotsuga menziesii*
Andic Cryochrept	8–60 (35)	1500–2400 (1524)	700–1500 (750)	*Abies lasiocarpa*
Andic Fragiboralf	0–30 (10)	680–850 (700)	710–889 (810)	*Tsuga heterophylla*
Region 4 (Idaho & Utah)				
Mollic Cryoboralf	5–70 (8)	800–1600 (914)	500–800 (760)	*Abies grandis*
Typic Cryumbrept	5–75 (45)	750–2000 (1068)	510–890 (640)	*Pseudotsuga menziesii*
Typic Cryaquent	2–35 (10)	2500–3080 (3048)	650–1000 (900)	*Pinus contorta*
Region 6 (Oregon & Washington)				
Pachic Ultic Haploxeroll	6–55 (15)	70–1833 (1500)	760–1520 (762)	*Abies grandis*
Typic Haploxerult	2–75 (15)	600–1700 (1500)	760–2160 (800)	*Pseudotsuga menziesii*
Andic Dystrudept	3–85 (10)	15–270 (15)	1525–2286 (1800)	*Picea sitchensis*

[a] Numbers in parentheses are the actual values used for WEPP modeling.

naturally occurring litter layer, whichever is less. We assumed no losses from the surface mineral soil.

Region 6 — *surface of mineral soil oxidized to a red color, and next 1.5 cm blackened due to charring of organic matter.* We assumed all the forest floor is destroyed, and 50% of the C, N, and CEC in the surface 1.5 cm of mineral soil is lost.

2.2.3. Erosion

Region 1 — *Rills, gullies, pedestals, and soil deposition are all indicators of detrimental surface erosion. Minimum ground cover maintained to produce <2–4 Mg ha^{-1} per year.*

Region 4 — *Establish local minimum ground cover guidelines to assure erosion does not exceed natural soil formation rate or soil-loss tolerance.*

Region 6 — *Visual evidence of surface loss, rills, gullies, and/or water quality degradation from sediment or nutrient enrichment. Erosion should not exceed natural soil formation rates.*

Mineral soil erosion losses were estimated with the Water Erosion Prediction Project (WEPP) model, which uses local climate, topography, and soil properties in its' calculation (Laflen et al., 1997).

Five WEPP estimates of soil erosion were obtained using a range of soil cover conditions that could occur after timber harvesting and site preparation. A hillslope length of 100 m was used in all calculations. The five scenarios are:

1. The upper 15 m of hillslope had a 10% surface cover, which often describes surface soil conditions after a wildfire or slash piling (Robichaud and Monroe, 1997). The remaining 85 m of hillslope was assumed to have a surface cover of 90%, which is found following a well-managed prescribed burn or after minimal mechanical site preparation. This combination represents the 15% minimum threshold for a soil to be considered detrimentally disturbed.
2. The entire 100 m slope has a surface cover of 10%. This value is an estimate of maximum erosion losses possible with this soil cover level.
3. The upper 15 m of slope has 50% soil cover, which represents a moderate amount of slash piling or moderate-intensity prescribed burn

Table 3
Average WEPP input values for the five scenarios used to estimate erosion in USFS Regions 1, 4, and 6.

Nominal surface cover (%)	Bulk density (g g^{-1})	Conductivity (mm h^{-1})
90	1.0	20
50	1.1	15
10	1.2[a]	10

[a] Increased to 1.3 g g^{-1} for Pachic Ultic Haploxeroll in Region 6.

(Robichaud and Monroe, 1997). The remaining 85 m of hillslope was assumed to have a surface cover of 90%.
4. The entire 100 m slope has a surface cover of 50%. This value is an estimate of maximum erosion losses possible with this soil cover level.
5. The entire 100 m slope has a surface cover of 90%. This value is an estimate of minimum erosion losses possible if this soil had best management practices applied.

Local climates were generated using the CLIGEN weather generator. Input values from stations in the CLIGEN database were adjusted to ensure that average annual precipitation of the stochastic climate was within 10% of the site climate. Annual precipitation and slope steepness used in the model is shown in Table 2. Table 3 presents the WEPP input values that were used for this evaluation. Soil bulk density and conductivity, taken from the NRCS profile analyses, were averaged for the three soils in each Region, since soil cover and annual precipitation have more influence in determining the WEPP outcomes (Elliot et al., 1995). To calculate C, N, and CEC losses from soil erosion we assumed that 1 mm of soil lost across an entire hectare weighs 8 Mg ha^{-1} (Robichaud and Brown, 1999).

3. Results and discussion

3.1. Total nutrient pools and distribution

As expected, the total amounts and distribution of soil C varied widely both within and among the three USFS regions (Table 4, Fig. 2A). Total C contents were highest in soils from Region 6 (146–

Table 4
Total C in forest floor and mineral horizons of representative soils from USFS Regions 1, 4, and 6, and possible losses if soil displacement and fire guidelines (>15% of the area) are exceeded

USFS region and soil subgroups	Horizon	Total C		Displacement loss		Fire loss	
		Mg ha^{-1}	%	Mg ha^{-1}	Total (%)	Mg ha^{-1}	Total (%)
Region 1							
Eutric Haplocryalf	Forest floor (5 cm)	55.0	58	8.3[a]–55.0[b]	–	8.3–55.0	–
	0–30 cm mineral	27.8	29	0.4–2.3	11–69	1.9–13.1	12–82
	Total to 1 m[c]	94.6	–	–	9–61	–	11–72
Andic Cryochrept	Forest floor (4 cm)	53.0	37	7.9–53.0	–	7.9–53.0	–
	0–30 cm mineral	66.5	47	0.8–5.5	7–49	1.7–11.3	8–54
	Total to 1 m	141.6	–	–	6–41	–	6–45
Andic Fragiboralf	Forest floor (3 cm)	46.0	28	6.9–46.0	–	6.9–46.0	–
	0–30 cm mineral	111.6	68	1.4–9.3	5–35	2.8–18.8	6–41
	Total to 1 m	165.1	–	–	5–33	–	6–39
Region 4							
Mollic Cryoboralf	Forest floor (5 cm)	38.0	36	5.7–38.0	–	2.8–19.0	–
	0–30 cm mineral	35.9	34	1.0–6.8	9–45	–	4–26
	Total to 1 m	104.8	–	–	6–43	–	3–18
Typic Cryumbrept	Forest floor (3 cm)	27.0	25	4.0–27.0	–	2.0–13.5	–
	0–30 cm mineral	51.6	47	0.8–5.0	6–41	–	3–17
	Total to 1 m	109.8	–	–	4–29	–	2–12
Typic Cryaquent	Forest floor (1 cm)	17.0	16	2.6–17.0	–	1.3–8.5	–
	0–30 cm mineral	46.6	43	0.3–2.1	5–30	–	2–13
	Total to 1 m	108.4	–	–	3–18	–	1–8
Region 6							
Pachic Ultic Haploxeroll	Forest floor (3 cm)	101.0	69	15.0–101.0	–	15.0–101.0	–
	0–30 cm mineral	31.5	22	0.8–5.7	12–80	0.2–1.1	12–77
	Total to 1 m	145.8	–	–	10–73	–	10–70
Typic Haploxerult	Forest floor (3 cm)	110.0	60	17.0–110.0	–	17.0–110.0	–
	0–30 cm mineral	37.0	20	1.4–8.9	13–81	0.8–5.3	12–78
	Total to 1 m	183.3	–	–	10–65	–	9–63
Andic Dystrudept	Forest floor (6 cm)	127.0	44	19.0–127.0	–	19.0–127.0	–
	0–30 cm mineral	101.8	35	6.0–37.0	11–72	0.6–4.3	9–57
	Total to 1 m	288.9	–	–	9–57	–	7–45

[a] Fifteen percent of the area is above threshold values.
[b] One hundred percent of the area is above threshold values.
[c] Total C in profile to 1 m, including the forest floor.

289 Mg ha^{-1}), and lowest in those from Region 4 (105–110 Mg ha^{-1}). Region 4 soils also had a much smaller percentage of C in the forest floor than Region 6 soils, which reflects generally thin litter layers in dry, fire-impacted Intermountain forests. Compared to Region 6, the forest floor in both Region 4 and Region 1 soils also had fairly high rock contents, which reflects a greater mixing with the mineral soil. Consequently, 3 cm of forest floor in the Typic Haploxerult (Region 6) contained considerably more C than 3 cm of forest floor in the typic Cryumbrept (Region 4) or in

the Andic Fragiboralf (Region 1). The surface 30 cm of mineral soils from Regions 1 and 4 generally had higher total C amounts and comprised a greater percentage of C pools than Region 6 soils.

In contrast to soil C, total N pools were much greater in the mineral soil than in the forest floor (Table 5, Fig. 2B), which reflects higher C:N ratios in the forest floor. The three Region 1 soils averaged the largest amounts of N (1306–10,593 kg ha^{-1}) due to the two Andic (ash-cap) soils used in this study. The characteristics of these ash-cap soils (few rocks, large
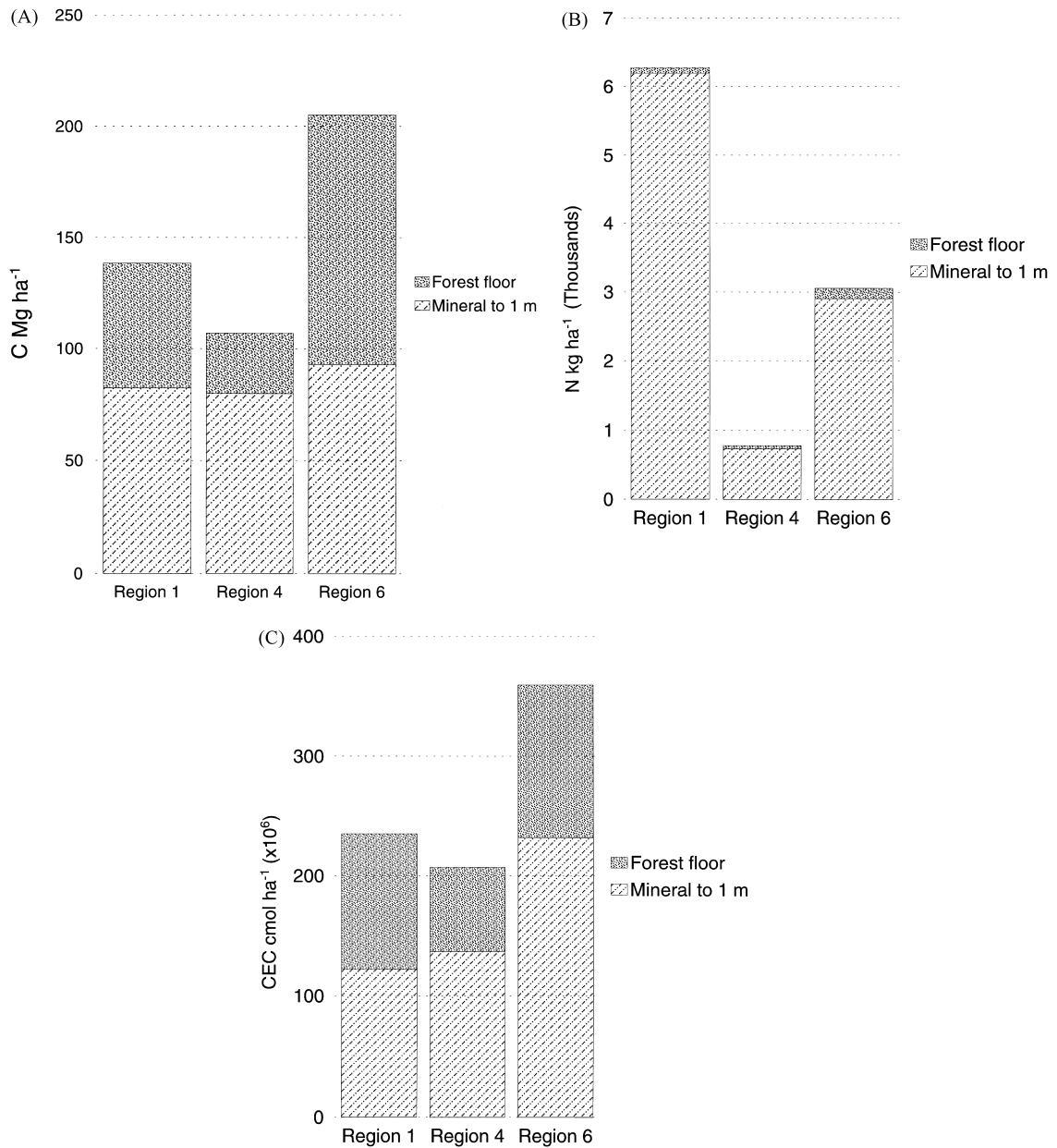
(A)

(B)

(C)

Fig. 2. Average distribution of (A) carbon, (B) nitrogen, and (C) cation exchange capacity in the forest floor and mineral soil (to a depth of 1 m) of three soils from USFS Regions 1, 4, and 6.

amounts of organic matter) combined with the relatively moist, cool climate of this Region enhances N storage within the profile (Shoji et al., 1993). Large amounts of N in the surface soil (0–30 cm) are particularly important for site productivity, since this is the

zone of greatest root activity (Kimmins and Hawkes, 1978; Little and Shainsky, 1992). However, storage of N and C at greater depths (30 cm–1 m) on some soils can also be important for long-term productivity (Henderson, 1995). The low amounts of N in Region

Table 5
Total N in forest floor and mineral horizons of representative soils from USFS Regions 1, 4, and 6, and possible losses if soil displacement and fire guidelines (>15% of the area) are exceeded

USFS region and soil subgroups	Horizon	Total N		Displacement loss		Fire loss	
		kg ha^{-1}	%	kg ha^{-1}	Total (%)	kg ha^{-1}	Total (%)
Region 1							
Eutric Haplocryalf	Forest floor (5 cm)	70	5	11[a]–70[b]	–	11–70	–
	0–30 cm mineral	587	45	7–49	3–18	39–261	8–50
	Total to 1 m[c]	1306	–	–	1–9	–	4–25
Andic Cryochrept	Forest floor (4 cm)	70	2	11–70	–	11–70	–
	0–30 cm mineral	3090	29	8–55	3–17	184–1230	6–41
	Total to 1 m	10593	–	–	0.1–1	–	2–12
Andic Fragiboralf	Forest floor (3 cm)	103	1	15–103	–	15–103	–
	0–30 cm mineral	5334	77	67–446	2–10	104–696	2–15
	Total to 1 m	6929	–	–	1–8	–	2–12
Region 4							
Mollic Cryoboralf	Forest floor (5 cm)	76	11	11–76	–	6–38	–
	0–30 cm mineral	239	46	6–38	5–36	–	2–12
	Total to 1 m	687	–	–	2–17	–	1–6
Typic Cryumbrept	Forest floor (3 cm)	35	6	6–35	–	3–18	–
	0–30 cm mineral	337	49	11–72	5–29	–	1–5
	Total to 1 m	693	–	–	2–15	–	1–3
Typic Cryaquent	Forest floor (1 cm)	30	3	5–30	–	2–15	–
	0–30 cm mineral	466	49	5–35	2–13	–	1–3
	Total to 1 m	953	–	–	1–7	–	1–2
Region 6							
Pachic Ultic Haploxeroll	Forest floor (3 cm)	170	5	26–170	–	26–170	–
	0–30 cm mineral	1883	52	51–338	4–25	19–127	2–15
	Total to 1 m	3599	–	–	2–14	–	1–9
Typic Haploxerult	Forest floor (3 cm)	169	11	25–169	–	25–169	–
	0–30 cm mineral	789	50	4–25	3–20	1.1–7.5	3–18
	Total to 1 m	1564	–	–	2–12	–	2–11
Andic Dystrudept	Forest floor (6 cm)	129	5	19–129	–	19–129	–
	0–30 cm mineral	1597	64	87–579	6–41	10–67	2–11
	Total to 1 m	2509	–	–	4–28	–	1–8

[a] Fifteen percent of the area is above threshold values.
[b] One hundred percent of the area is above threshold values.
[c] Total N in profile to 1 m, including the forest floor.

4 soils are likely related to the high fire-incidence in these dry forest ecosystems.

Soil CEC values of the soils from all Regions follow the same trends as soil C levels (Table 6, Fig. 2C) with a large proportion of total CEC found in forest floor horizons. Typically, soil CEC increases with increasing organic matter content, clay content, and pH (Meyer et al., 1994). However, there is little quantitative information on CEC in forest soils, particularly the contribution of forest floor layers to overall soil exchange capacity (Wells and Davey, 1966; Kalisz and Stone, 1980).

3.2. Application of soil quality standards

3.2.1. Soil displacement

Application of USFS Regional soil displacement standards illustrates the disparity of conditions that could be found in different soils after stand disturbance activities. Disturbance impacts on soil productivity are dependent on the type of soil in the harvest operations area and the location of organic matter in the soil profile (Tables 4–6; Fig. 2). Consequently, soils with more C or N in the forest floor (Region 6) are more affected by displacement than soils with

Table 6
Total CEC in forest floor and mineral horizons of representative soils from USFS Regions 1 4, and 6, and possible losses if soil displacement and fire guidelines (>15% of the area) are exceeded

USFS region and soil subgroups	Horizon	Total CEC		Displacement loss		Fire loss	
		$cmol_c\ ha^{-1}$ $(\times 10^{-6})$	%	$cmol_c\ ha^{-1}$ $(\times 10^{-6})$	Total (%)	$cmol_c\ ha^{-1}$ $(\times 10^{-6})$	Total (%)
Region 1							
Eutric Haplocryalf	Forest floor (5 cm)	100.0	57	15[a]–100[b]	–	15–100	–
	0–30 cm mineral	39.6	23	0.6–4	11–76	0.6–4	11–76
	Total to 1 m[c]	174.4	–	–	8–61	–	8–61
Andic Cryochrept	Forest floor (4 cm)	150.0	67	23–150	–	23–150	–
	0–30 cm mineral	39.5	18	0.5–4	12–82	0.2–1	12–80
	Total to 1 m	225.5	–	–	10–68	–	10–67
Andic Fragiboralf	Forest floor (3 cm)	90.0	41	14–90	–	14–90	–
	0–30 cm mineral	76.1	35	1–7	8–58	0.5–3	8–56
	Total to 1 m	219.8	–	–	7–44	–	7–42
Region 4							
Mollic Cryoboralf	Forest floor (5 cm)	60.0	20	9–60	–	5–30	–
	0–30 cm mineral	41.5	14	5–35	9–45	–	5–29
	Total to 1 m	132.5	–	–	6–43	–	2–9
Typic Cryumbrept	Forest floor (3 cm)	80.0	52	12–80	–	6–40	–
	0–30 cm mineral	32.2	21	1–6	12–77	–	5–36
	Total to 1 m	152.7	–	–	9–56	–	4–26
Typic Cryaquent	Forest floor (1 cm)	70.0	42	11–70	–	5–35	–
	0–30 cm mineral	44.7	27	0.5–4	10–64	–	4–31
	Total to 1 m	167.6	–	–	6–44	–	3–21
Region 6							
Pachic Ultic Haploxeroll	Forest floor (3 cm)	110.0	34	17–110	–	17–110	–
	0–30 cm mineral	73.9	23	1–9	10–65	0.2–2	9–61
	Total to 1 m	325.2	–	–	6–37	–	5–34
Typic Haploxerult	Forest floor (3 cm)	120.0	45	18–120	–	18–120	–
	0–30 cm mineral	55.6	21	1–7	11–72	0.8–6	11–72
	Total to 1 m	268.4	–	–	7–47	–	7–47
Andic Dystrudept	Forest floor (6 cm)	150.0	31	23–150	–	23–150	–
	0–30 cm mineral	97.7	20	4–27	11–71	1–7	9–64
	Total to 1 m	483.4	–	–	6–37	–	5–32

[a] Fifteen percent of the area is above threshold values.
[b] One hundred percent of the area is above threshold values.
[c] Total CEC in profile to 1 m, including the forest floor.

lower amounts (Regions 1 and 4). The degree of C and N loss also depends on the areal extent of disturbance on a given site. For all three Regions, current threshold guidelines assume displacement of the entire forest floor and some mineral topsoil will have no detrimental impact on soil productivity if it occurs on <15% of the area. If this minimum detrimental displacement threshold of 15% is applied to each soil, C losses range from 5 to 11% in Region 1, 3–9% in Region 4, and 9–10% in Region 6 for the soil profile to a depth of 1 m (Table 4). These C losses are only a few

percent higher for total pools to a 30 cm mineral soil depth. When soil disturbance is assumed to cover the entire area (100%), C losses in all three Region 6 soils are >55% to a 1 m soil depth, and >70% to a 30 cm depth.

Total N displacement losses followed a pattern similar to C in soils from all three Regions (Table 5). However, due to high C:N ratios in the forest floor, the percent of total N pool losses are much less than found with soil C. When N losses are calculated for the minimum detrimental disturbance

threshold (15% of the area) in all three Regions, they are <6% of total N pools at 30 cm or 1 m soil depths. Even with a 100% soil disturbance, overall N losses are <40%.

Since soil organic matter is an important source of CEC, organic matter displacement greatly affects soil CEC values. In these three Regions, approximately 1/3–1/2 of the total soil CEC is found in the forest floor (Table 6). However, when soils have appreciable clay contents in the mineral soil horizons, such as in Regions 4 and 6 soils, surface organic matter losses would have less impact on total soil CEC pools and potential nutrient leaching losses from subsoil horizons. Displacement losses of CEC in soils from the three regions were 6–10% (to a depth of 1 m) if the areal extent of disturbance is limited to 15%. Loss of CEC and its impact on sustainability is difficult to measure because most information is fragmented, anecdotal, and method-dependent (Meyer et al., 1994). However, loss of surface CEC can lead to increased leaching losses of nutrients throughout the profile.

While many studies have reported the effects of harvesting and other site disturbances on soil organic matter and nutrient levels, very few give information which can be compared to the displacement guidelines used in this study. Piling all logging residues, forest floor, and ≈2.5 cm of surface mineral soil into windrows (≈100% displacement) reduced volume growth of *Pinus radiata* in New Zealand by 16% after 7 years, as compared to a unwindrowed site (Ballard, 1978). In North Carolina, windrowing (which usually removes 75–90% of the surface organic matter from the harvest area (Gresham, 1991)) of a Typic Hapludult caused a 23% reduction in volume growth after 25 years (Fox et al., 1989). On a cutover site in Interior British Columbia, with 17% of the cut area occupied by skid roads (with total organic matter removal), height growth of planted *Picea engelmannii* and *Pinus contorta* seedlings planted on the skid roads was 28 and 14% less than seedlings planted in undisturbed (forest floor intact) areas (Senyk and Craigdallie, 1997). On an Andic Fragiboralf soil in northern Idaho (similar to the Region 1 soil used in this study), displacement of surface organic matter and mineral topsoil to 3 cm on 25% of the harvest area resulted in reduced total N, mineral soil organic matter content, and CEC. Seedlings (*Pinus monticola* and *Pseudotsuga menziesii*)

planted on the displaced areas showed a reduction of 30% in height after 3 years as compared to seedlings planted in areas where the forest floor was intact (Page-Dumroese et al., 1997).

In contrast, some studies have shown that displacement of forest floor and some surface mineral soil can improve early seedling growth (Sloan and Ryker, 1986; Miller, 1991; Barnard et al., 1995; Bulmer et al., 1998). Seedling survival and growth after forest floor removal can increase due to better planting conditions, increased soil moisture from reduced vegetative competition, or decreased disease incidence (Cole, 1988; Barnard et al., 1995; Powers and Fiddler, 1997). However, these short-term gains may, or may not, be indicative of longer-term tree growth.

In all these studies the reported growth responses could be caused by soil displacement, soil compaction by logging or site preparation equipment, or a combination of the two. The relative importance of these two soil disturbance factors is being addressed in the North American Long-Term Soil Productivity Study, which mimics harvesting and site preparation extremes to help delineate soil quality threshold guidelines for soil monitoring (Powers et al., 1990). Preliminary results from a northern Idaho site on an Andic Fragiboralf (Table 4) indicates forest floor loss did not change seedling height growth for the first 5 years after harvesting, but compaction level did (Page-Dumroese, preliminary data). However, on this site, buried logs (within the mineral soil profile) occupy ≈20% of the soil surface and may be the reason for limited response to forest floor loss. Buried logs are not currently part of the monitoring guidelines. However, their importance on this site (and others) should be evaluated since it appears that early seedling survival and growth may benefit from their presence in the soil profile.

3.2.2. Detrimental burn conditions

Historically in the northwestern USA and western Canada, fire has been used as a site preparation tool to manage for early successional species, such as western larch (*Larix occidentalis* Nutt.) (Arno and Fischer, 1995). The hotter the fire (usually associated with slash pile burning or wildfires), the greater the destruction of organic matter (Harvey et al., 1994; Robichaud and Waldrop, 1994). According to Regions 1 and 6 soil quality burning guidelines, the entire forest floor and

appreciable organic matter in the A horizon must be lost before detrimental soil conditions are assumed to occur. In contrast, detrimental impact in Region 4 would occur if only 5 cm or 1/2 of the forest floor is lost (Table 1). A lower forest floor loss threshold was established in Region 4 because forest sites in this region are often fire-dominated which results in shallow organic horizons and low soil nutrient pools (K. Johnson, personal communication). Consequently, detrimental soil impacts in Region 4 would occur in soils with much lower levels of organic matter loss.

For all three Regions, minimum threshold fire effects (15% of the area) on total C pools result in a fairly small loss of 1–12% (Table 4). In Regions 1 and 6, C losses from fire on 100% of the area would be very similar to surface displacement, with C declines of 41–82%. In contrast, soil C threshold losses from fire in Region 4 soils are much less than soil displacement, ranging from 1 to 19 Mg ha^{-1} (Table 4). Although total profile C (to 1 m) losses are slightly less than for the surface 0–30 cm, they can be substantial if large areas are impacted.

Applying the detrimental burning thresholds to Regions 4 and 6 soils would result in less soil N losses than would occur with detrimental soil displacement (Table 5). Such differences in detrimental soil N losses between the two guidelines may be justified since most N lost from burning is volatilized into the atmosphere, while at least some of the N moved by displacement is still on the site and available for plant uptake. In contrast, soils such as the Region 1 Andic Fragiboralf, which has a large proportion of N in the top 30 cm of mineral soil, are more susceptible to N losses from fire than from displacement.

Nitrogen losses from fire vary depending on the intensity of fire and the amount of surface and mineral soil organic matter destroyed (DeBano et al., 1979; DeBano, 1979). These N losses after fire may not be as high as previously reported since some N may move from the forest floor into deeper mineral soil layers (Covington and Sackett, 1992). Mroz et al. (1980) also pointed out that generalizations about fire effects on N in soils with different forest floor characteristics may not be useful or valid. Many studies in the Pacific Northwest have reported a wide range of soil N losses following prescribed fire, depending on the amount and type of surface organic matter, and burning con-

ditions (Jurgensen et al., 1981; Monleon and Cromack, 1996), and decreased N supply has been linked to a decline in overall stand productivity (Landsberg et al., 1984). However, similar to studies on soil displacement, these results have not been related or compared to soil quality guidelines, so it is not possible to use them to validate or modify threshold limits.

Since organic matter is the major source of CEC in all these soils, loss of forest floor layers from fire has a large impact on soil CEC content (Table 6). Such fire losses would be particularly critical in coarse-textured soils with low organic matter content, such the Typic Cryumbrept (Poff, 1996). Since the burn threshold for Region 4 requires, at most, loss of only half the forest floor layer, compared to complete removal of the forest floor in Regions 1 and 6, detrimental CEC losses from Region 4 soils would be much less than soils in the other Regions.

3.2.3. Soil erosion

Soil erosion standards as written for Regions 1 and 4 are indistinct and fundamentally untestable, although the areal extent is similar to the other standards (15% for detrimental disturbance). In addition, neither slope steepness nor vegetation cover are addressed in the Soil Quality Standards for Regions 1 or 4. Region 6 has developed an erosion hazard classification which describes the minimum effective ground cover (live or dead) needed to limit soil erosion for various erosion hazard classes, but it is not soil-type specific. Rather, this classification system is a synthesis of intrinsic properties (organic matter, soil texture, and aggregate stability) and extrinsic properties (slope, rainfall, and slope length). Soils are mapped independently of erosion hazard classification (R. Meurisse, personal communication). Soil quality thresholds of soil erosion in all three regions are primarily based on visual evidence of rills, gullies, pedestals, and loss of ground cover developed locally (with limits set at the rate of soil formation). Unfortunately, local guidelines have not been formulated for most forests.

Since detailed threshold values were not available for soil erosion, we selected five different erosion scenarios using the WEPP model (see Section 2) to show possible sediment yields (sediment delivered to the bottom of each slope) (Table 7). The WEPP model

Table 7
Mean annual sediment yield from representative soil from USFS Regions 1, 4, and 6 by applying various cover percentage scenarios

USFS region and soil subgroups	Sediment yield (Mg ha^{-1})				
	10% top and 90% bottom soil cover[a]	10% soil cover[b]	50% top and 90% bottom soil cover[c]	50% soil cover[d]	90% soil cover[e]
Region 1					
Eutric Haplocryalf	1.5	44.7	1.0	12.3	0.3
Andic Cryochrept	0.4	15.7	0.8	5.0	0.8
Andic Fragiboralf	0.3	26.4	0.5	0.7	0.4
Region 4					
Mollic Cryoboralf	0	0	0	0	0
Typic Cryumbrept	0	12.9	0	0.1	0
Typic Cryaquent	0	0	0.1	0	0.1
Region 6					
Pachic Ultic Haploxeroll	<0.1	0	0.1	1.0	<0.1
Typic Haploxerult	0	0	0.2	0	0.3
Andic Dystrudept	<0.1	4.9	0.1	0	<0.1

[a] The upper 15 m of hillslope had 10% cover the remaining 85 m had 90% cover.
[b] Entire 100 m hillslope had 10% cover.
[c] The upper 15 m of hillslope had 50% cover the remaining 85 m had 90% cover.
[d] Entire 100 m hillslope had 50% cover.
[e] Entire 100 m hillsope had 90% cover.

does not calculate forest floor losses, so values shown are for mineral soil only. It is assumed that forest floor is removed by other site disturbances (e.g., displacement, fire) prior to erosional loss.

Like soil displacement and detrimental burning, there are major differences among soils both within and among the three Regions. It does not always follow that sites with the most annual precipitation or greatest slope (see Table 2) have the greatest sediment yield (Table 7). For Region 1, the scenario which represents the minimum detrimental area disturbance threshold of 15% (10% cover on the top 15 m of the site and 90% cover on the bottom 85 m of the 100 m hillslope) produced very little sediment (<1.50 Mg ha^{-1}). At this level of soil cover, the threshold value of loss (2–4 Mg ha^{-1} per year) was not exceeded in any of these three soils. However, considerable variability was found among the three soils at higher disturbance levels, with the Eutric Haplocryalf showing the greatest erosion losses. As expected, sediment production was usually least with 90% cover and most with 10% cover. Low levels of disturbance (50% cover on the top 15 m and 90% cover on the bottom 85 m of the 100 m hillslope) also resulted in <1 Mg ha^{-1} sediment.

The WEPP model generated very little sediment in Region 4 soils using our five scenarios either because of gentle slopes, coarse-textured soils (allowing greater infiltration), or both. However, the Region 4 Mollic Cryoboralf soil was also part of the North American Long-Term Soil Productivity study (Powers et al., 1990), on which erosion losses of 4.5 Mg ha^{-1} were measured after complete forest floor removal (equivalent to the 10% soil cover scenario) and no soil compaction (Elliot et al., 1998). These losses exceed the average natural soil formation rate for forest soils of 2.5 Mg ha^{-1} per year (Troeh et al., 1980) that is outlined in the Region 4 guidelines. When the forest floor alone or forest floor and tree crowns were left on the soil surface (with no compaction), sediment production downslope was <2.0 Mg ha^{-1} (Elliot et al., 1998). Differences in sediment loss between our scenario (Table 7) and the field study may be due to model assumptions of infiltration and conductivity. These differences also underscore the variability between model predictions and collected data.

Soil loss is only one problem associated with accelerated erosion. We also examined loss of C, N, and CEC that might be associated with sediment loss. In Region 1, C losses are at a maximum when soil

Table 8
Mean total C and N lost in sediment using five erosion scenarios on soils from USFS Regions 1, 4, and 6

USFS region and soil subgroups	10% top and 90% bottom soil cover[a]		10% soil cover[b]		50% top and 90% bottom soil cover[c]		50% soil cover[d]		90% soil cover[e]	
	C (Mg ha^{-1})	N (kg ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})
Region 1										
Eutric Haplocryalf	<0.1	4	0.5	11	<0.1	2	0.2	3	<0.1	<1
Andic Cryochrept	<0.1	<1	0.4	20	<0.1	1	0.2	<1	<0.1	1
Andic Fragiboralf	<0.1	<1	1.2	59	<0.1	1	<0.1	5	<0.1	1
Region 4										
Mollic Cryoboralf	0	0	0	0	0	0	0	0	0	0
Typic Cryumbrept	0	0	0.3	2	0	0	<0.1	<1	0	0
Typic Cryaquent	0	0	0	0	<0.1	<1	0	0	<0.1	<1
Region 6										
Pachic Ultic Haploxeroll	<0.1	<1	0	0	<0.1	<1	0.1	<1	<0.1	<1
Typic Haploxerult	0	0	0	0	<0.1	<1	0.1	0	<0.1	<1
Andic Dystrudept	<0.1	<1	0.2	3	<0.1	<1	0	0	<0.1	<1

[a] The upper 15 m of hillslope had 10% cover the remaining 85 m had 90% cover.
[b] Entire 100 m hillslope had 10% cover.
[c] The upper 15 m of hillslope had 50% cover the remaining 85 m had 90% cover.
[d] Entire 100 m hillslope had 50% cover.
[e] Entire 100 m hillslope had 90% cover.

cover is 10% (Table 8), but never exceed 1% of the total C pool. At all other disturbance levels C loss was estimated as <1% of the total profile. In Region 4, only the minimum cover scenario (10% on the 100 m hillslope) for the Typic Cryumbrept showed any C loss. For this same ground cover scenario, the Andic Dystrudept in Region 6 lost 0.2 Mg ha^{-1} total C from the profile, but is also <1% of the total C pool. Displacement (9–72%) and fire (7–57%) losses for all study soils are much higher (Table 4) because they also included the forest floor losses.

Erosional soil N losses follow similar trends as C and are a small fraction of the total mineral soil N pools. Depending on soil cover, N losses in Region 1 soils range from <1 to 59 kg ha^{-1} (Table 8), but these values represent <2% of the total profile N. Nitrogen losses from Region 4 soils are much less than those from Region 1 soils (N loss was 2 kg ha^{-1} from the Typic Cryumbrept), and maximum N loss in Region 6 soils was 3 kg ha^{-1}. Soils from these two Regions also had low sediment production. For all three Regions, total CEC loss from soil erosion was <1% of the profile CEC. This reflects the low proportion of

CEC in the mineral soil, compared to the organic forest floor horizons.

4. Suitability of regional soil monitoring guidelines

It is increasingly evident that forests will be harvested under a planned sustainable forest regime (Amaranthus, 1998). Under such management plans harvest and site preparation activities require accurate monitoring of site impacts to maintain soil productivity. Forest soils are inherently variable; some are resilient to harvest activities, while others are at risk of losing their productive capacity after harvesting because of a shallow forest floor or thin mineral mantle over bedrock (Burger and Kelting, 1998). Application of soil quality guidelines from three USFS Regions highlight the variability that can occur when detrimental impact thresholds are uniformly used within a Region. For instance, we estimated displacement loss of C for one Region 1 soil to vary from 11–69% of its' total C pool (to 1 m) while

another soil lost 5–35%, depending on how much of the site was disturbed. However, productivity losses from displacement, while initially high in localized areas, may not be as significant to site sustainability as fire or erosion. Displacement does not mean forest floor and topsoil is lost from the site, only moved from one place to another. In contrast, organic matter volatilized by fire is lost from the site. Burning also can cause development of a hydrophobic layer shallow in the soil profile, which can increase the risk for substantial soil erosion (Robichaud and Waldrop, 1994; Poff, 1996).

Erosion rates are usually highest immediately after site disturbance and loss of both soil and nutrients are usually one to two orders of magnitude less by the second year (Robichaud and Brown, 1999). This raises the question of when to measure erosion rates; should the assessment be done immediately postharvest when erosion could be high, or should it be done after the site has had a year to rejuvenate some ground cover? Certainly, the timing of monitoring activities will yield different assessments. This question is not defined within the guidelines as they are written, but needs to be addressed. Accelerated erosion rates will remove topsoil and deposit it lower on the slope (where microsite productivity may be increased), or offsite (stream, road) where it is removed from producing vegetation (Elliot et al., 1998). Both of these result in overall declines in site productivity on at least a portion of the eroded slope because of loss of nutrients, rooting depth, and available water holding capacity (Lal et al., 1998).

Relatively small disturbances (15% of the area) of the study soils from all regions appear to result in relatively small losses of C, N, CEC, and sediment from a site (1–13% of total pools) and, at these levels, current guidelines seem to be adequate. However, as the areal extent of disturbance gets larger, our analyses indicate that substantial losses in C, N, and CEC pools can occur. In addition, cumulative effects from successive disturbances are not directly addressed in the guidelines. Extremes in site treatment (i.e. severe burns or displacement of topsoil) indicate where gross changes in soil properties are usually noticed. However, the dividing line between when a treatment is detrimental or not must still be refined. It is not known how much organic matter must be lost from each of the soils in Table 3 to have a detrimental effect on soil productivity, but one can assume that the greater the organic matter loss, the greater the impact on soil productivity. Once organic matter is removed, its recovery and successive increases in C, N, or CEC is often slow on many Inland Northwest soils, often taking >50 years (Clayton and Kennedy, 1985). In addition, cumulative effects of several small disturbances, which result in progressive organic matter losses over many rotations, may lead to long-term degradation of soil productivity (Sollins et al., 1980; Dyck et al., 1994; Tiarks and Haywood, 1996). Decaying logs within the soil profile may help mitigate some management effects, but to date, this component of forest ecosystems is not tallied as part of the soil quality monitoring effort.

Since the forest floor is an important source of C, N, and CEC for all of the soils we evaluated in this study, application of the Regional guidelines for displacement or burning means appreciable losses in these soil pools are sometimes acceptable. However, based on our evaluations and other research studies, it is difficult to establish definitive organic matter loss values and associated changes in site productivity. One of the problems we encountered in accumulating soil-specific information was obtaining accurate estimates of undisturbed forest floor depth. This data is not commonly collected in stand surveys and standard soil pedon descriptions rarely contain this information. However, this is a crucial and easy-to-collect piece of information which is required to estimate detrimental impacts of displacement, erosion, or fire on important soil properties such as total C, N, or CEC.

Our study emphasizes the importance of site-specific information and that blanket threshold values are not the optimum solution. Improvement of soil monitoring efforts and forest management practices comes from measurement of site- and soil-specific information before silvicultural prescriptions are delineated. Relatively few research studies have linked their results to specific soil quality threshold values. This offers forest managers little chance to refine existing guidelines or develop new ones. Site-specific guidelines, developed in conjunction with modeling efforts (i.e. WEPP, etc.) is one step. The WEPP model (Laflen et al., 1997) represents the best current understanding of soil erosion by water in forested situations. Using this type of model to determine erosion severity from a site after disturbance activities can be an effective tool

if it is also linked to soil or stand productivity data. Monitoring at various times (i.e. to assess erosion changes) during the stand rotation (immediately post-harvest, crown closure, thinning, etc.) may also help understand changes in stand productivity (Burger and Kelting, 1998).

Development of more quantitative soil quality monitoring guides should incorporate some pre-disturbance hazard assessment using data on slope, hydrology, soils, and especially climate, which is usually the most important factor for controlling organic matter accumulations and decomposition (Powers, 1999). Slope and percent ground cover is used in Region 6 to assign a soil erosion rating the first or second year after a site is harvested. In British Columbia an erosion hazard rating is developed by assigning point values for: general climatic zones, slope gradient and length, depth to water table, texture, coarse fragments, and soil permeability (Forest Practices Code of British Columbia, 1995). Development of similar hazard rating protocols for soil displacement and detrimental burning may improve prediction of downslope sediment delivery.

The importance of soil monitoring to evaluate disturbance effects on soil productivity is widely accepted and mandated through numerous laws and initiatives. It is, therefore, essential to establish soil quality monitoring variables that are practical to use, give meaningful information over a wide range of sites, and provide a benchmark for evaluating soil change. Adequate baseline assessment of important site-specific properties like soil strength or bulk density, forest floor depth, soil cover, etc. will help make accurate and realistic projections of potential site productivity losses (or gains) from various soil disturbances. In addition to the collection of soil impact information, research studies need to link measured soil variables to those used in current soil monitoring criteria. This connection is crucial to the development of more accurate, site-specific soil quality guidelines.

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